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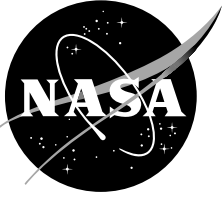
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Summary

In many aerospace activities, human error is a significant problem with potentially serious consequences. Reduction and mitigation of such errors are important goals of both the Aviation Operations Systems and Safety programs and of the Space Human-Factors program. A critical thrust of these programs is to develop new quantitative, yet non-intrusive, metrics of human perceptual performance that can be used in applied settings to monitor performance in real time and to facilitate training. This study is part of an effort within the Human Information Processing Research Branch at Ames Research Center to develop metrics of human visual performance based on eye-movement monitoring. Given that visual search is a critical component of many aerospace tasks (e.g., monitoring aircraft display icons by an air traffic controller), we have developed metrics based on signal-detection theory to relate the eye-movement and perceptual data during a search task.

Traditional studies of saccadic targeting have examined how visually guided saccades to unambiguous targets are programmed and executed. In visual search, however, it has been less clear to what extent human saccades are visually guided as opposed to driven by *a priori* expectations or preprogrammed sampling strategies. In this study, we estimated the visual information used for the first saccade during a search for a target disk in noise at several levels of saliency. A signal-detection-theory metric (d') allowed us to make quantitative comparisons between the accuracy of the first saccadic decision and the associated final perceptual decision at the end of the search. We found that, at all levels of saliency tested, the first saccade uses visual information from the current display to select its target. At the highest saliency tested, the information used for the first saccadic decision approaches that used for the final perceptual decision, indicating that a sustained search was unnecessary. We also quantified the performance enhancement obtained with eye movements by comparing

the accuracy of perceptual decisions made with and without the benefit of saccades. We found that the enhancement is large at low saliency, but insignificant at high saliency. Our findings highlight the need to vary saliency when examining perceptual and/or saccadic visual information processing. We conclude that signal-detection theory can provide a common framework for making meaningful quantitative comparisons between perceptual, oculomotor, and potentially even neural data, thereby providing a powerful tool for future search studies.

Introduction

Humans make frequent rapid eye movements (saccades), to point the high-resolution fovea at the location of current interest. A fundamental question is how the brain decides when to make a saccade and where to direct its endpoint, a process known as saccadic targeting. One visual task for which saccades are likely to play a particularly important role is search. Most studies of search have, however, only measured perceptual performance (i.e., reaction times and percentage of correct trials when looking for a target object hidden among distractor objects). Far less is known about saccades during active visual search.

Studies of human saccadic targeting have left unresolved the extent to which saccades are guided by currently displayed visual information versus cognitive expectations, prior experience, or other *a priori* strategies (refs. 1-6). The present study focuses on estimating the visual information about target location in the current display that contributes to the targeting of the first search saccade. We compare quantitatively both saccadic and perceptual performance to the theoretical optimal by calculating the absolute efficiency. This allows the direct comparison of the visual processing for saccadic targeting, a visuomotor decision, with that for perceptual decisions. In addition, most previous oculomotor search studies have used high-saliency "popout" targets for which perceptual decisions are nearly always correct. Because saliency is known to affect perceptual decisions during search, there is reason to suspect that saccadic decisions will also be affected. We therefore measure saccadic decision accuracy at three levels of saliency. Finally, given that saccades are

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a critical component of natural search behavior, our third goal is to quantify the performance enhancement achieved by active search with eye movements over passive search during fixation.

Methods

Stimuli were viewed binocularly on a Philips brilliance 21A monitor, luminance linearized using a look-up table. On each trial, the target, a 21 in. diameter gaussian-blurred ($\sigma = 3.5'$) disk appeared with equal probability at the center of one of 10 boxes ($2.4^\circ \times 2.4^\circ$) equidistant along a radius of 5.9° (fig. 1A). Gaussian-distributed, spatially uncorrelated (white) luminance noise was added to each pixel (RMS contrast = 26% and mean luminance 35 cd/m²). Target (signal) contrast was adjusted to achieve three different saliencies or signal-to-noise ratios (SNRs): 2.99, 5.19, and 7.26.

Observers started each trial by fixating a small cross. With a mouse press, they then triggered the presentation of a “test image” (fig. 1A), and with another mouse press, they indicated when they found the target. After responding or after 6 s (whichever came first), the test image was replaced by a “response image” that contained the 10 empty boxes and a rotatable central arrow. Observers used mouse buttons to point the arrow toward their 10-alternative forced choice (10 AFC) and to record their decision.

In the “eye-movement” condition, observers were allowed to make eye movements, but no specific eye-movement strategy was encouraged. In the “fixation” condition, observers were instructed to fixate the central cross at all times during the trial. Observers participated in three sessions, each consisting of six runs of 100 trials performed in pseudo-random order. Each run consisted of a single block of a particular SNR and condition. Eye movements were monitored to record saccade endpoints, to discard trials with anticipatory saccades (<90 ms latency) in the eye-movement condition and trials in which observers broke fixation (1.7° threshold) in the fixation condition. Because of the parametric nature of the experiments and the consistency across observers, data were only collected from the three authors, each with normal vision.

The position of the left eye was measured using an infrared video-based eye tracker sampling at 240 Hz (ISCAN Inc., NASA prototype), synchronized with the 60-Hz monitor. Calibration was performed using nine crosses arranged in a 12° by 12° grid (precision $<0.2^\circ$). Head movements were minimized using a bite bar. The eye position from the initial trial fixation was used to correct for any small residual head movements on each

trial. Saccades $>0.7^\circ$ were detected using a digital template.

To facilitate the comparison of the first saccadic decision with a perceptual 10 AFC, the saccadic endpoint was assigned to one of the 10 possible targets. We initially explored two criteria. The “distance or direction” criterion considered the first saccade correct if its endpoint was closer to the target than to any of the distractors. The advantage of this criterion is that it uses the true first saccade without penalizing for saccadic hypometria, e.g., the first saccade in figure 1B is deemed correct by this criterion. The disadvantage is that a correct saccade could correspond to a deliberate saccade to a non-target, non-distractor location. The “box” criterion considered the first saccade that landed inside a box. It was deemed correct if the box contained the target. The advantage of this second criterion is that it corresponds to an unambiguous target selection. The disadvantage is that the measured performance does not necessarily correspond to the true first saccade, e.g., the second saccade in figure 1B is the correct saccade for this trial by this criterion. Paired t-tests, however, showed no significant difference between these criteria ($p < 0.05$, Bonferroni corrected). We therefore define saccadic decision accuracy using the direction criterion.

Results

Accuracy Analysis

Figure 2A shows the accuracy of the first saccadic decision (open symbols) and of the final perceptual decision (solid symbols) in the eye-movement condition. Final perceptual accuracy was always significantly higher (t-test, $p < 0.05$) than initial saccadic accuracy (except for LS at the highest SNR), and both increased with increasing SNR. The SNR effect cannot be accounted for by a speed-accuracy trade-off because both perceptual reaction times and saccadic latencies increased with decreasing SNR (from 0.9 to 3.6 s and from 217 to 264 ms, respectively, averaged across observers). Figure 2B shows the final perceptual accuracy with (solid symbols) and without (open symbols) eye movements. Perceptual accuracy was always significantly higher ($p < 0.05$) in the eye-movement condition than in the fixation condition at the lower two SNRs, but not at the highest SNR. On average, reaction times were faster in the fixation (~ 2.2 s) than in the eye-movement (~ 3.6 s) condition at the lowest SNR. However, the performance enhancement from saccades cannot be entirely attributed to speed-accuracy trade-off because, in a control experiment which imposed a 4 s viewing time in both conditions at the lowest SNR,

eye movements still dramatically increased performance (measured as d' , see below) on average by 32%.

Efficiency Analysis

To allow meaningful quantitative comparisons between perceptual, saccadic, and ideal decisions, we transformed percent correct into the d' index of detectability, defined as the distance in standard deviation units between the target and distractor response distributions (using a lookup table for a 10 AFC, see ref. 7). Unlike direct comparisons of percent correct, the squared d' ratios (efficiencies) provide quantitative measures of the relative performance viewed as information, independent of the number of distractors (ref. 8). Absolute efficiency specifies performance relative to the ideal observer. The d'_{ideal} is simply the SNR (in the case of white noise, the square root of the sum of the squared target-pixel contrasts divided by the noise contrast standard deviation, see ref. 9). The absolute efficiency of the first saccade, $(d'_{\text{saccade}} / d'_{\text{ideal}})^2$, ranged from 4 to 20% (across observers and SNRs) while that of the final perceptual decision, $(d'_{\text{perceptual}} / d'_{\text{ideal}})^2$, ranged from 20 to 38% (eye-movement condition) and from 10 to 33% (fixation condition). The relative efficiency of the first saccadic versus final perceptual decision, $(d'_{\text{saccade}} / d'_{\text{perceptual}})^2$, increased with SNR and reached a mean of 60% (across observers) at the highest SNR (fig. 3A, solid symbols). The relative efficiency of the final perceptual decision in the fixation versus that in the eye-movement condition also increased with SNR, reaching a mean of 104% at the highest SNR (fig. 3B).

To examine further the low relative efficiency at lower SNRs in figure 3A, we performed a short-duration control experiment at SNR = 4.15. Because the first saccade can only use information gathered during the saccadic latency minus the ~100 ms needed for motor programming (ref. 3), we measured the perceptual decision 100 ms before the observer's median saccadic latency. The mean relative efficiency of the first saccade versus the time-matched perceptual decision was then at or near unity (83.6%, $p \sim 0.08$, fig. 3A, open symbols), ruling out any large inefficiency in saccadic information processing relative to perception.

Discussion

Our data show that the decision accuracy of the initial search saccade was better than chance for all observers at all levels of saliency tested. We used statistical decision theory to estimate the information in the display available to the first saccade, and to compare perceptual and saccadic performance to the theoretically optimal. The absolute efficiency of the initial saccadic decision in our task was

4-20% which can be directly compared to behavioral performance in other tasks, e.g., 10-56% for disk detection in noise (ref. 8; this study), 70% for contrast discrimination (ref. 9), 12-20% for letter identification (ref. 10), and 3-8% for object recognition (ref. 11).

Examining a range of saliencies is vitally important when studying information processing during search and its associated oculomotor behavior. Our results demonstrate that saliency strongly affects the accuracy of the first saccade and the impact of eye movements on search performance. At low saliency, the relative efficiency of the first saccade versus the final perceptual decision is quite low, while at high saliency, it is closer to unity. Furthermore, by restricting perceptual processing to the time available for the first saccade, we show that low relative efficiency at low SNR is not entirely due to inefficient visual information processing for saccades. In addition, our results show that the eye-movement enhancement of search performance is prominent only at low saliency. These results show that only at low saliency does information about target location greatly increase as the search progresses, both by the increased processing time and by the (near) foveation of potential targets.

Physiological Implications

The performance limits of the first saccade during search must reflect neural information about target location. A number of cortical and subcortical areas have been implicated in saccadic targeting, most notably, the frontal eye fields (FEF), the superior colliculus, and the parietal cortex. For example, FEF responses appear to play a role in target selection during search (ref. 12); collicular responses appear to reflect the spatial uncertainty in target location (ref. 13); and responses in the lateral intraparietal cortex appear to reflect the salience or behavioral relevance of potential saccadic targets (ref. 14). Within this context, we propose a tool that could be used to compare saccadic targeting with neural and perceptual responses using the same metric. The ability of a neuron (or neuronal population) to locate the target could be estimated by computing its d' from the mean and standard deviation of its target and distractor responses. The neural d' could then be directly compared to those of saccadic and perceptual decisions. This method is similar to the ROC analysis (ref. 7) used by others to compare neural activity with psychophysical response times (ref. 15). Although our analysis is restricted by the testable assumption that response distributions are gaussian, it is considerably simpler and more versatile.

Human-Factors Implications

This study proposes an oculometric analysis of human saccadic eye movements during search that can be used to provide quantitative measures of both the role and effectiveness of searching eye movements in the detection process, and of the rate of information acquisition about target location over time and over successive saccades. The preliminary validation of our methodology presented here provides strong motivation for additional studies of human visual performance to extend our understanding of the role of eye movement in human visual performance in aerospace-related tasks and to determine when eye-movement metrics provide an accurate measure of human perception. This study of saccadic eye movements complements our parallel investigation of the relationship between smooth eye movements and motion perception (refs. 16, 17).

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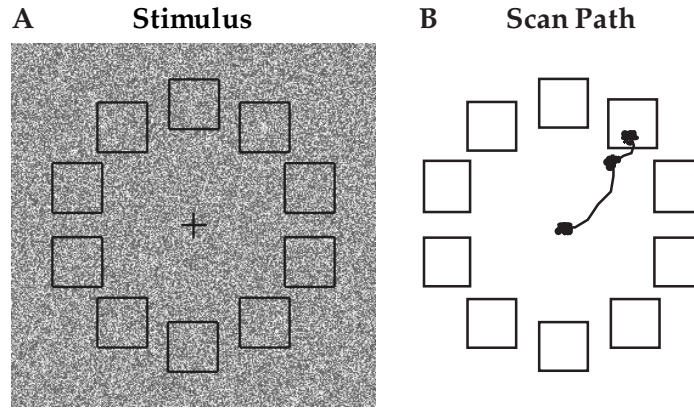


Figure 1. A. Example of high-SNR stimulus. B. Scan path of a single high-SNR trial for observer ME, illustrating the first two search saccades (thin lines) and fixations (cluster of eye-position samples).

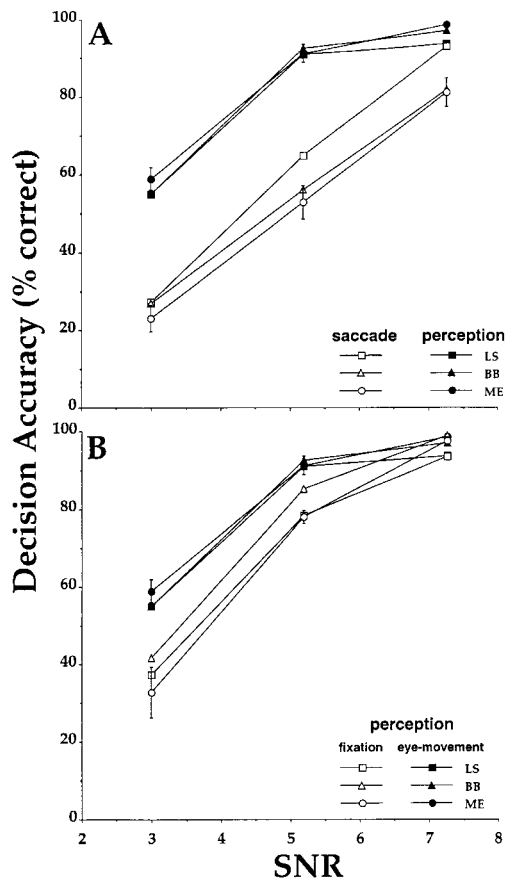


Figure 2. A. Accuracy of the first saccadic and final perceptual decisions. B. Accuracy of the final perceptual decision with and without eye movements. For clarity, here and in figure 3, error bars (SEM) are not presented for all observers. Random guessing would produce 10% accuracy.

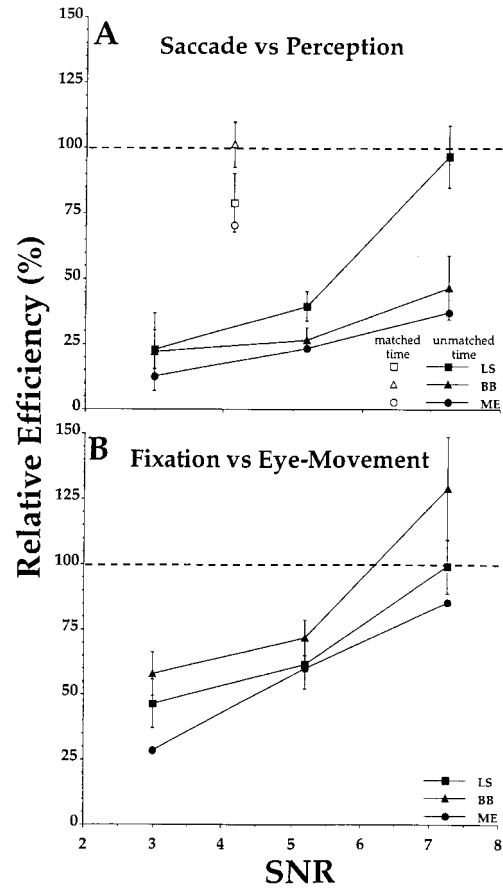


Figure 3. A. Relative efficiency of the first saccade versus the perceptual decision after up to 6s (solid symbols) and after a short presentation restricted to match saccadic visual processing time (open symbols). B. Relative efficiency of the final perceptual decision in the fixation condition versus that in the eye-movement condition. Dashed lines indicate equal efficiency.

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